The monitored performance of the combination of balanced ventilation with post-conditioning by an air-to-air heat pump

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ABSTRACT

A balanced ventilation system can be combined with an air-to-air heat pump. Such system combines the refreshment of the air in a house with heating and cooling of the fresh air in order to influence the indoor conditions like temperature and humidity. Depending on the season in the year, various modes are used to deliver fresh air and condition the incoming air to the desired levels.
Field tests with such a ventilation system were carried out in houses in Luxembourg and in Italy. The monitored data has been analysed to give meaningful views of the performance. Correlations between supply temperatures and outdoor temperatures show modes of the system with heat recovery, cold recovery or passive cooling combined with active heating or active cooling when needed. The data shows that the system is first attempting to heat or cool with passive means, after which active heating or cooling is used when necessary.
The desired indoor temperatures are based on a temperature profile as a function of the prevailing mean outdoor temperature, following the adaptive comfort guidelines. The resulting thermal output as well as the required electrical consumption are given. Energy signatures show the daily thermal output as a function of the daily averaged outdoor temperatures. These energy signatures also show the resulting heating season, intermediate season and cooling season. The threshold of the heating and cooling season is dependent on the demands of the residents, but also on geographical location, orientation of the house and insulation properties.

KEYWORDS

Balanced ventilation, smart ventilation, postconditioning, air-to-air heat pump, energy signature

1 INTRODUCTION

The heating of residential dwelling has been common since long. Cooling of dwellings is a technology that is growing in use because of global warming and better insulation. The use of mechanical ventilation is also growing because dwellings are renovated or built with a higher level of airtightness and insulation. In fact, adequate ventilation needs to be considered in houses when implementing energy efficiency measures of the dwelling, as stated by the European Commission (2021).
Most of these technologies are developed in different time periods in the near history, so that dwellings have separate products for heating, for cooling and for ventilation.
This study examines the practical performance of a combined system for ventilation, cooling and heating. This technology aims to bring fresh, filtered air to a house but also has the ability to change the indoor air temperature by cooling or heating the incoming fresh air. This postconditioning can operate as single source of cooling and heating in nearly zero-energy buildings, or it can be added during renovation to existing technologies for heating and cooling. According to Ortiz et al. (2020), the energy transition is mainly to be realized by using a combination of building-related energy efficiency measures, renewable energy systems and their related distribution systems.

2 MONITORING SET-UP

Two dwellings on two locations in Europe were monitored (see fig. 1), one in Italy and one in Luxembourg.
The house in Italy was situated near Modena (humid subtropical climate zone). It was built in 2017 and consists of 3 floors with total floor area of 270 m^2. The insulation was within Passive House limits with a U-value of 0.132 W/m^2K for the walls and 0.123 W/m^2K for the roof. There were no other heating or cooling units used, other than the technology in this study.
The other house in Luxembourg (oceanic climate) was built in 1981 and renovated in 2020 with a total floor area of 185 m^2. Typical U-values for this house were 0.14 W/m^2K for the walls and 0.20 W/m^2K for the roof. A floor heating is installed in the house but during the monitoring year it was never used. A bathroom radiator has sometimes been used.

a) 
b) 

Figure 1: The monitored houses in Italy (a) and in Luxembourg (b). The building in Italy is a double house where the left side is equipped with the technology under study and is the subject of monitoring.

The new technology in this study (Zehnder, ComfoAir Q + ComfoClime Q system in fig. 2) is a combination of a balanced ventilation system with post-conditioning by an air-to-air heat pump. The post-conditioning is a dehumidifying/cooling function during the warmer months of the year and a heating function during the colder periods. The performance of the whole system is explained in the following paragraphs and the schematic picture in fig. 3.

Figure 2: A photo of the installed system in the house in Italy.

During the cold periods of the year, the temperature of the fresh air from outside is first brought close to the indoor temperature by the heat recovery (avoided heating). When there is a heat request in the house, the air-to-air heat pump will further increase the temperature of the fresh air (postheating).
During the warmer months, with temperatures outside warmer than inside, the cold recovery decreases the temperature of the fresh air close to indoor level (avoided cooling). When there is a cooling request in the house, the air-to-air heat pump will further decrease the temperature of the fresh air (postcooling). The postcooling is resulting in fresh air that is cooled both in a sensible way (temperature decrease) as in a latent way (moisture decrease).
During the periods of the year with mild temperatures, the recovery is automatically decreased or totally shut off (bypass activation) depending on the actual measured and desired temperatures. This ensures passive cooling, also called ventilative cooling when the conditions are favourable.

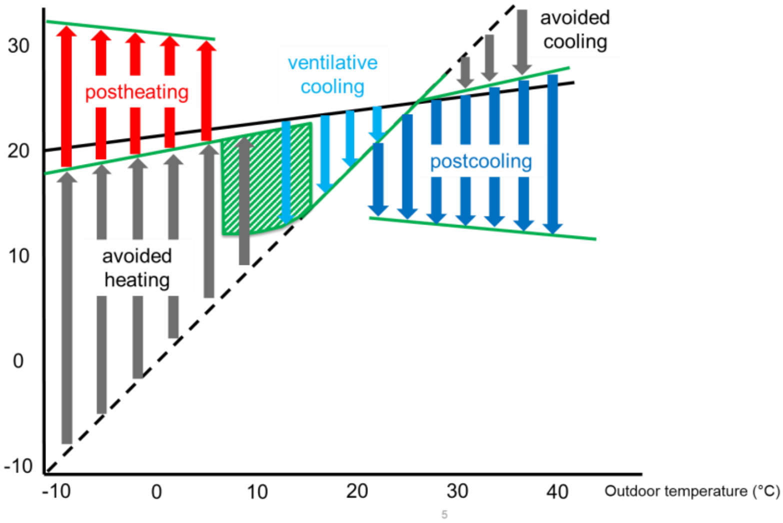


Figure 3: Schematic representation of the working principle. Black line: temperature of indoor air, green line: temperature of supply air (possibly after postconditioning)

Data of the performance of this technology is monitored with built-in sensors in the installation. These parameters include temperatures (outdoor, supply after recovery, supply after postconditioning, extract and exhaust), humidities (outdoor, supply after recovery, extract and exhaust), flow characteristics of both supply and extract air stream (flow rate, fan speed, fan duty), and electrical consumption. All parameters are recorded during a full year (18 July 2021 until 17 July 2022) every five minutes and afterwards summarized in hourly averages for further analysis.

3 RESULTS

3.1 Cooling effect on indoor climate

The cooling effect of the installation on the indoor climate in summer can be demonstrated by the performance during a couple of consecutive summer days.
Fig. 4 shows two weeks with outdoor temperatures ranging between 30°C and 33°C during days and 20°C-25°C during nights. During the first five days the ventilation system including recovery was active, but the postcooling had not been commissioned yet. The supply temperature during the day was brought to the indoor level (effect of cold recovery), but the extract temperature remained on a high level with extract temperatures up to 30°C. During

nights, the bypass was activated to bring in the cool outdoor air, with the supply air close to the outdoor air.
After five days (6 September 2021) the postcooling was commissioned. The air-to-air heat pump brought the supply air to an approximate level of 15°C. The cooling effect on the indoor climate can be seen during the course of a couple of days, with gradual decrease of extract temperatures. After four or five days, the extract temperature had reached the desired setpoint of 22°C and remained at that level.

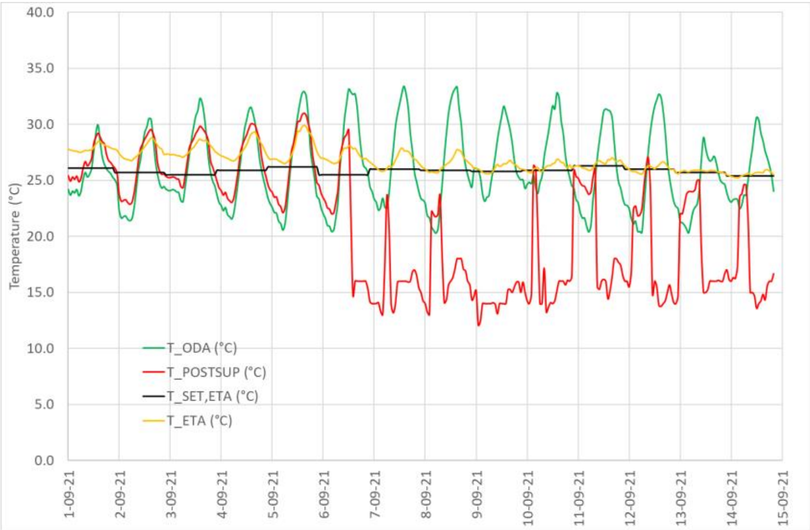


Figure 4: Cooling effect of the system before and after activation of postcooling. Lines indicate temperatures of outdoor air (green), supply air after postcooling (red), extract air (yellow) and setpoint for extract (black).

3.2 Operation modes during the seasons of a year

The monitored performance in the dwellings in Italy and in Luxembourg can be observed in the temperature correlations in fig. 5.
In Italy, extract temperatures ranged from 22°C in winter to 27°C in summer. In Luxembourg, extract temperatures ranged from 20°C in winter (excluding holidays when postheating was disabled) to 25°C in summer. In Italy, both postheating and postcooling had been used, while in Luxembourg postcooling was hardly necessary.
Various operation modes can be observed, depending on actual and desired conditions:

1. heat recovery with postheating
2. heat recovery (no heating request, e.g. during nights)
3. ventilative cooling (bypass activated)
4. ventilative cooling with postcooling
5. cold recovery (no cooling request, e.g. during nights)
6. cold recovery with postcooling

The various operation modes ensure comfortable supply temperatures, following the demands in the various seasons. There is one period with an exception because of technical problems. In Italy, one sensor had an error during two winter months (20 Nov ’21 – 25 Jan ‘22). Therefore, flow balance was disrupted and heat recovery efficiency was lower than expected. This is visible during winter nights with supply temperature below 20 °C (during nights there was no postheating requested).

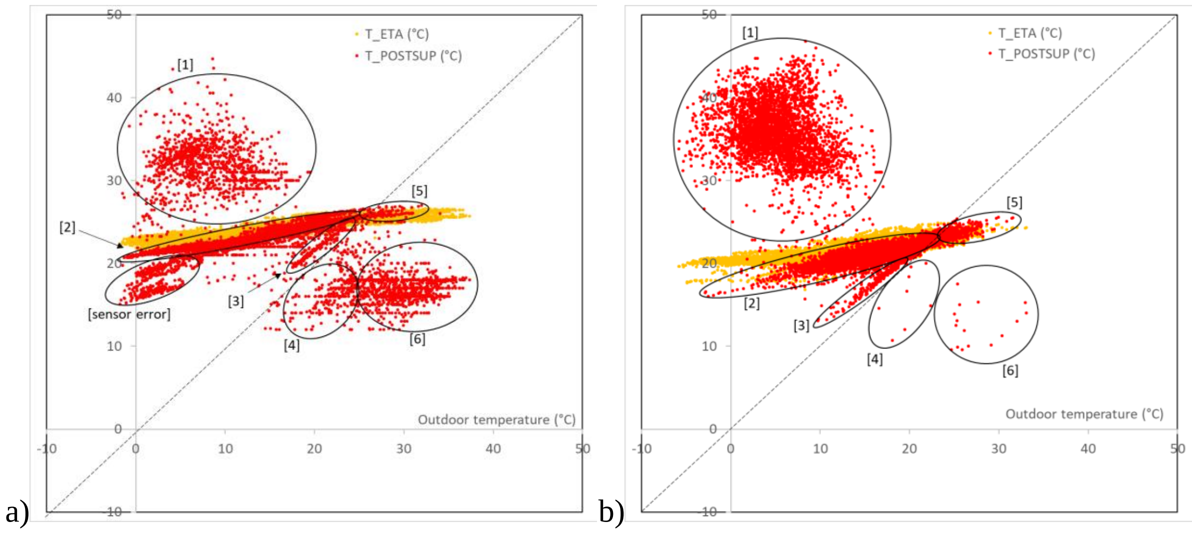


Figure 5: Temperature correlation of supply air (red) and extract air (yellow) as a function of outdoor temperature for the house in Italy (a) and in Luxembourg (b)

The various operation modes are automatically chosen by the control algorithm based on actual and desired conditions, because it is hard for residents to find the optimal operation mode themselves (Spiekman, 2022). They follow the “Trias Energetica” (see fig. 6), meaning that first the energy demand is reduced, then natural energy resources are used and as a last step active heating and cooling technologies with minimal electricity consumption are used (Verbeeck, 2010).

During the part of the year with mild outdoor temperatures, and when there is a cooling request, the system can either bring ventilative (free) cooling, or it can postcool using electricity from the heat pump compressor. The algorithm of this technology is written in such a way that with cooling request first the ventilative cooling [mode 3] is used (with cool outdoor air, or fresh air that is precooled by a ground heat exchange system). Only when after a while the indoor temperature is not decreasing, the postcooling is started [mode 4] along with the ventilative cooling to ‘help’ cool the indoor air.

When outdoor temperatures surpass indoor temperatures, first the heat is kept out by cold recovery [mode 5], and when indoor stays too warm the postcooling starts [mode 6].

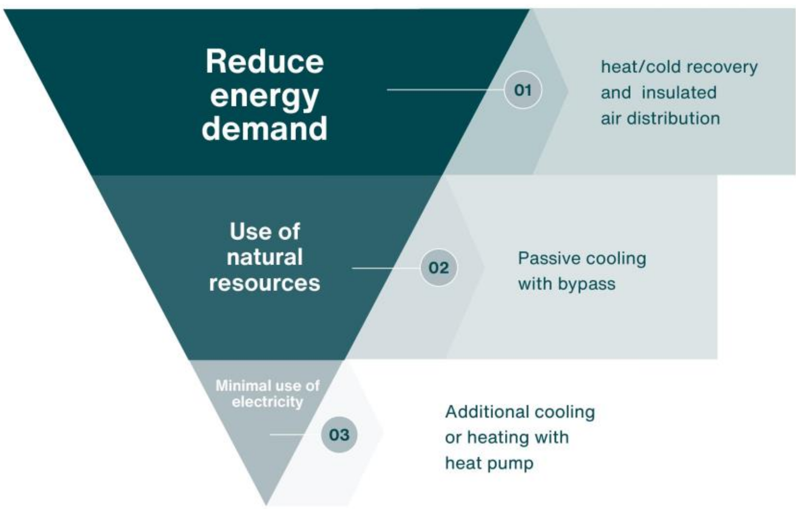


Figure 6: The concept of the Trias Energetica and the implementation for balanced ventilation with postconditioning by an air-to-air heat pump

3.3 Desired indoor temperature profiles according to adaptive comfort

The desired indoor temperature inside dwellings depends on geographical location, characteristics and orientation of the building, and on user preferences. Predefined profiles in the system of study are not constant throughout the year. They are constant during the heating season, but during the intermediate seasons and the cooling season, they vary with a mean outdoor temperature. The predefined temperature profiles may be set and changed by the residents of the dwelling according to their preferences.
Fig. 7 shows the desired indoor temperature as a function of the prevailing mean ambient temperature T_{pma}. In Italy, the setpoint for the indoor temperature is constant at 23.5°C during the heating season (T_{pma} < 10°C). During the intermediate season, the setpoint gradually increases with increasing T_{pma}. This follows the adaptive comfort technology and allows residents to gradually get adapted to warmer temperatures in the outdoor as well as in the indoor environment. In the cooling season, the residents have opted for a constant setpoint of 24.5°C. In Luxembourg, during the heating season (here: T_{pma} < 14°C) the setpoint is constant at 21°C. During the intermediate season the setpoint increases with the T_{pma} to a level of 23°C. There was a change in desired temperature profile setting at 21 February 2022, after which the setpoint of temperature increased about 0.5°C over the entire range of T_{pma}.

a) b)

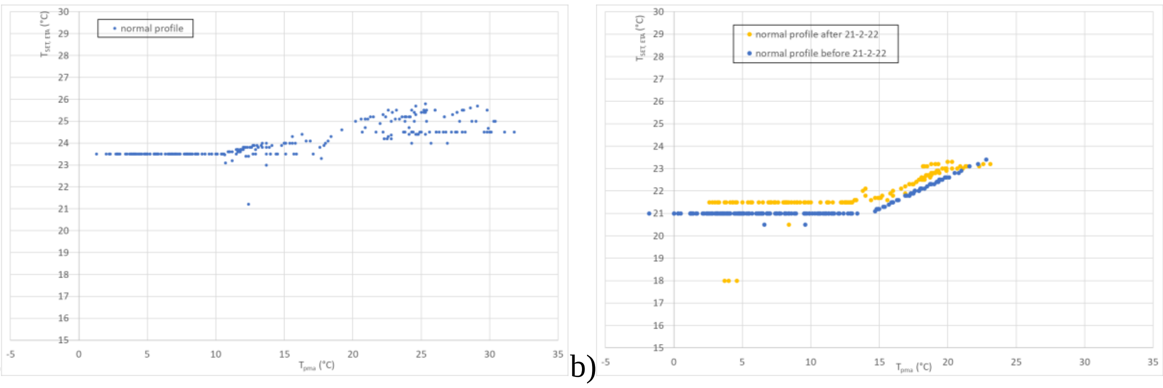
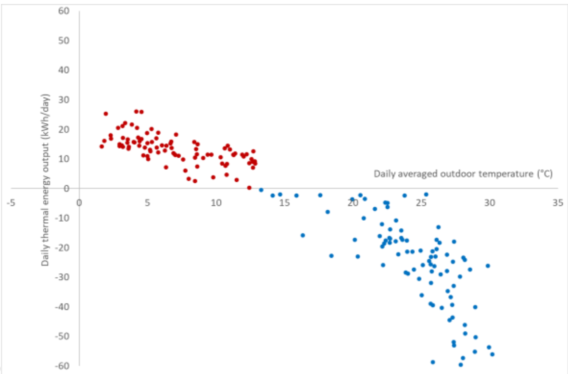


Figure 7: Desired indoor temperature as a function of the prevailing mean ambient temperature T_{pma} for the house in Italy (a) and in Luxembourg (b). During the course of the year, the residents sometimes change the settings, which - in the case of the house in Luxembourg - has been indicated with blue and yellow dots.

3.4 Energy signatures

From the temperature, humidity and flow data, the thermal output has been calculated. In Italy, the typical flow rate was 300 m^3/h, but lower values of 190 m^3/h occurred during night settings and higher values until 480 m^3/h when there was more heating or cooling demand to condition the indoor climate. In Luxembourg, the typical flow rate was 200 m^3/h, but lower values of 80 m^3/h were used with no occupation and higher values until 300 m^3/h when more heating or cooling was required.
Attention should be taken which data to use for calculation of thermal output. The thermal output which has been calculated in this study is the conditions of the supply air after postheating or postcooling compared to the supply air before postcooling or postheating (in fig. 3 this is represented by the difference between the two green lines during postcooling or postheating). The calculated thermal output with these numbers is aligned with the thermal output of the air-to-air heat pump. As such, it gives an idea on the thermal output of the system to actually cool or heat the dwelling.

In fig. 8, energy signatures for the system in Italy and in Luxembourg are given. An energy signature displays the daily thermal energy output as a function of the daily averaged outdoor temperature. Postheating is displayed as positive numbers in red, and postcooling is displayed as negative numbers in blue. Both energy signatures show an increasing thermal heating output in the heating season with decreasing average outdoor temperature, as expected. Variation in the numbers can arise from a varying solar thermal gain, from occupation variation and from the chosen daily scenario. A daily scenario can be chosen to reduce or block the heat pump during a part of the day, for instance at night. The Italian house also shows a pronounced cooling season where the thermal cooling output (sensible plus latent) increases with increasing average outdoor temperature.
Comparing the house in Italy with the house in Luxembourg, one can conclude that the house in Italy needs roughly half the energy to heat the house, although the floor area is larger and the setpoint is higher (23.5°C) than in Luxembourg (21-21.5°C). In Italy, heating is necessary until the average outdoor temperature has reached a level of 13°C. In Luxembourg, heating is still necessary until the average outdoor temperature has reached a level of 16°C.

a)


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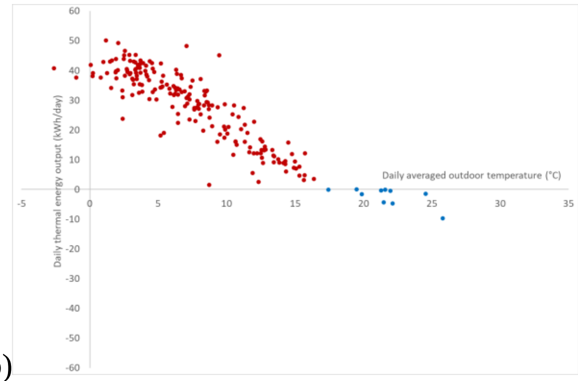

Figure 8: Energy signatures (daily thermal energy output as a function of daily averaged outdoor temperature) for heating in red and for cooling in blue for the house in Italy (a) and in Luxembourg (b).

4 DISCUSSION

The combination of balanced ventilation with postconditioning with an air-to-air heat pump is a comprehensive technology for providing fresh air in a comfortable and energy-efficient way. This study demonstrates the cooling effect of the heat pump during summer days. As shown, it takes a couple of days for a very warm house to cool down to comfortable temperatures, after the cooling has been switched on for the first time. After the indoor climate has been cooled down, the heat pump can work with lower thermal input to remain at a comfortable cool environment. When outdoor temperatures are lower than indoor temperatures (e.g. at night), the bypass activation ensures the use of ventilative cooling, possibly complemented with active cooling by the heat pump.
Temperature correlations between the (conditioned) supply air and the outdoor temperature shows a variety of modes in which the system operates. During cold days, fresh air is delivered comfortably warm using heat recovery, possibly postheated by the heat pump to give useful heating to the house. During warm days the opposite takes place: fresh air is delivered comfortably cool, possibly postcooled by the heat pump to give useful cooling to the house. For mild outdoor temperatures, the mode which is automatically selected is dependent on the actual measured conditions and the desired indoor conditions. Recovery can take place, but also ventilative cooling can take place. In favourable conditions even ventilative heating is taking place but this is a rather unusual situation (bringing warm outdoor air into a house that is not warm enough yet).

The frequency distribution of the various modes is dependent on the outdoor climate (geographical location), on the building characteristics (such as insulation type and orientation with respect to the sun) and on the residents' preferences (desired indoor temperature). The differences between the Italian house and the house in Luxembourg are obvious. In Luxembourg, postcooling is rarely needed, but postheating is used much more often.

Energy efficiency of the system is safeguarded following the Trias Energetica. The energy load is kept low by heat recovery during cold periods and cold recovery during warm periods of the year. Because of the recovery, the outdoor temperatures have been mitigated to levels close to the indoor temperature. From that level, the heat pump can either postheat or postcool in an efficient way to deliver the thermal energy to the house. During favourable conditions, natural energy sources can provide thermal energy to the house. These natural energy sources can be the outdoor air itself, or for instance energy stored in the ground or even in district heating or waste heat networks.

The desired indoor temperature profile is not constant throughout the year, but varies with the average outdoor temperature (more specifically with the prevailing mean ambient temperature T_{pma}). A consequence is that during warm periods of the year, the desired indoor temperature does not stay on a very low level. By allowing the indoor temperature to gradually move along with the increasing outdoor temperature, the body is prevented from "thermal boredom". This means the indoor climate allows the body to get used to differences in temperature (Van Marken Lichtenbelt, 2021). Moreover, a constant setpoint leads to excessively high cooling demands in summer. In view of the global energy reduction, but also for lower cooling costs for residents, an adaptive comfort profile is preferable to a constant temperature profile.

The energy signatures of the house in Italy and in Luxembourg show fairly linear profiles of the energy input as a function of outdoor temperature. The angle of the linear profile with the horizontal axis is expected to be dependent on the total floor area, on the orientation of the house and the insulation characteristics. The intersection of the profile with the horizontal axis is probably most dependent on the preferences of the resident. Important factors are the desired indoor temperature (adaptive comfort profile) and the decision of the resident to stop the postconditioning from taking place at a certain outdoor temperature threshold.

The size of the heat pump in combination with the flow rate decides the maximal thermal input that can be delivered to the house. Whether this is sufficient for maintaining the desired indoor temperatures, depends on the insulation characteristics of the house. In practice, this means that this technology as stand-alone system is suitable for providing fresh air and postconditioning in nearly zero-energy buildings and Passive House buildings. In existing buildings or buildings with limited insulation characteristics, this technology can serve as addition cooling and/or heating source for the building while providing sufficient and constant fresh air.

5 CONCLUSIONS

This study shows the monitored performance of a balanced ventilation system with postconditioning by an air-to-air heat pump. The monitoring has taken place in two houses with different insulation characteristics, and in two different outdoor climates; one in Italy and one in Luxembourg.

The performance shows that this technology can provide a comfortable indoor climate throughout the year, with comfortable supply temperatures of the fresh air. The technology works in an energy-efficient way making use of reduction of energy demand, use of natural energy resources and use of the heat pump only when necessary.

Future work will be carried out on the thermal energy output compared to the electricity input in order to define the energy efficiency of the technology.

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